PUBLICATIONS
OF THE
Astronomical Society of the Pacific.

Vol. XXX. San Francisco, California, December, 1918 No. 178

THE PRESENT CONDITION OF THE PROBLEM OF SOLAR ROTATION

By Charles St. John

Since the classic investigations of Duner, begun in 1898, in which he applied the Doppler-Fizeau principle to the problems of solar rotation, the spectroscopic method has been accepted as the one promising with the greatest probability solutions of the various questions that have arisen. The possibility of its application was indicated by Vogel's observations in 1871. The first measurements of the displacements of the solar lines at the Sun's equatorial limb due to rotation were made by Young in 1876. Later Langley and Cornu showed that by this method lines due to absorption in the Earth's atmosphere could with ease and certainty be distinguished from lines of solar origin. The displacement of solar lines at the Sun's limb relative to atmospheric lines observed by Langley and Cornu gave direction to Duner's investigation and to that of Halm. Both observers used the iron lines γ6301 and γ6302 and referred them to the closely adjacent atmospheric lines and both made visual observations only.

In 1906 Adams began an extensive series of spectro-photographic determinations. The great advantages of the photographic observations are the possibility of using a far larger number of lines and of covering a greater spectral region and the inclusion of a wide range of elements and of line intensities, as observations are no longer restricted to the visual spectrum. Since the work of Adams, photographic methods have been universally employed and investigations of solar-rotation problems have been carried on in European, Indian, Canadian, and American observatories.

The question first attacked was naturally the fundamental one of the absolute velocity of the reversing layer at different latitudes. Halm raised the question of periodic variation in the rate of rotation, and Adams found decided differences for high and low levels in the solar envelope. The point upon which general agreement

seems to have been reached is that the relative velocities at different latitudes are quite satisfactorily represented by the empirical formulae of Faye, more nearly so than by any other suggested. The values of the coefficients found by the different observers are given below. These values are sometimes approximate as the results were not all given in this form originally.

Observed Coefficients of the Formulae of Faye

	Daily Angular Velocity	Linear Velocity, km. per Second	Date
Duner	$\xi = 10^\circ.60 + 4^\circ.21 \cos^2\phi$	$V = (1.49 + 0.59 \cos^2\phi) \cos\phi$	1900.5
Halm	$12\ .03 + 2\ .50 \cos^2\phi$	$(1.66 + 0.39 \cos^2\phi) \cos\phi$	1904
Adams	$11\ .04 + 3\ .50 \cos^2\phi$	$(1.55 + 0.50 \cos^2\phi) \cos\phi$	1907.8
DeLury	$10\ .04 + 3\ .70 \cos^2\phi$	$(1.45 + 0.52 \cos^2\phi) \cos\phi$	1911
Plaskett, J. S.	$10\ .53 + 3\ .71 \cos^2\phi$	$(1.49 + 0.52 \cos^2\phi) \cos\phi$	1911–12–13
Schlesinger	$10\ .77 + 3\ .40 \cos^2\phi$	$(1.52 + 0.48 \cos^2\phi) \cos\phi$	1912
Plaskett, H. H.	$10\ .23 + 3\ .81 \cos^2\phi$	$(1.44 + 0.54 \cos^2\phi) \cos\phi$	1913

While the respective formulae represent fairly well the observations of the individual investigators, the coefficients show discrepancies that require further consideration. The differences in the coefficients depend of course upon the linear velocities and these in turn upon the observed line displacements.

The data relative to the linear velocity at the solar equator are accumulating from year to year and now extend over a period of twenty-one years. A review of the results is of interest. The data are assembled in the following table.

Linear Velocity of Solar Rotation at the Equator

Observer	Velocity	No. of Lines	Region	Date
Duner	2.08	2	6301—6302	1900.5
Halm	2.04	2	6301—6302	1904
Adams	2.06	20	4196—4294	1907
Adams	2.05	22	4196—4291	1908.5
Storey and Wilson	2.08	10	6280—6318	1909
Plaskett, J. S.	2.01	19	5506—5688	1911
Plaskett, J. S.	2.02	15	4196—4291	1911
DeLury	1.97	19	5506—5688	1911
Hubrecht	1.86	40	4299—4400	1911
Plaskett, J. S.	2.01	27	4250—5600	1911–12–13
Schlesinger	2.00	20	4058—4276	1912
Evershed and Royds	1.95	..	3906—5624	1913
Plaskett, H. H.	1.98	12	5574—5628	1913
Ware and St. John	1.94	35	4123—4338	1914
Plaskett, H. H.	1.95	5	5900	1915
Ware and St. John	1.94	26	5018—5316	1914–18
Ware and St. John	1.95	7	6265—6337	1916–17

There is a striking difference between the first and second halves of the twenty years under consideration, a difference showing slight, if any, evidence of regular progression, appearing almost per saltum near the end of the first decade and becoming increasingly evident at the end of the series. Halm thought he found evidence of a three-year period by combining his own and Duner's observations, but no subsequent observer has found confirmation of it. The supposition that at once comes to mind is that a change in the solar rotation might be associated with the sun-spot cycle, owing to the varying activity in the solar envelope. Spot maxima occurred in 1906 and 1917. The corresponding equatorial velocities were 2.05 km. and 1.94 km., nearly extreme values. On the face of these results there is no evidence of any general change connected with spot activity.

As the differences in velocity appearing in the table are much larger than can be attributed to accidental errors of measurement, we are forced to seek some other explanation. Local disturbances due to the presence of spots near the points of observation were noted by Adams, and effects of local currents in the atmosphere have been suspected by others. Some recent observations at Mount Wilson have shown that with the large solar image (diameter 425 mm.) the integrating action of the spectroscope is so reduced that local conditions obtaining over very limited regions of the solar surface may introduce differences exceeding those appearing in the table. The prism system receiving light from the opposite edges of the solar image consists of three prisms each 2 mm. in height, the two outer prisms taking light from one edge, the middle one from the other edge. By rotating the spectrograph, the east and west edges are interchanged with respect to the prism system. It was thought that by such an interchange a valuable check upon the observations could be had, but frequently differences of several per cent appeared upon plates taken in immediate succession. These differences were at first suspected to be instrumental, but, when recourse was had to the red region of the spectrum, where atmospheric lines could be used for reference, it was found that the results for solar lines differed greatly from plate to plate, tho atmospheric lines were undisplaced. Well defined and isolated solar lines were selected for measurement. The mean deviation for the individual lines from the mean velocity given by a single plate is less than 0.005 km., while the velocities given by different plates

occasionally differ by 0.15 km. In view of the precision of measurement and the non-displacement of the atmospheric lines these large differences seem attributable only to solar causes.

It is evident that a limited series of observations may lead to misleading results and it becomes a question whether the solar rotation can be determined as definitely as has been anticipated. The mean from a long series of observations should represent, however, a fairly well determined average, and, as the observations upon which the results in the table are based extended in most cases over months and sometimes years, it seems hardly probable that local disturbances would introduce systematic differences of such magnitude, and it seems even less probable that a rapid change in solar rotation occurred near the middle of the two decades.

Personal characteristics of the measurer may doubtless introduce systematic errors, but as yet evidence sufficient to justify one in ascribing the differences between the extremes of the table to personal equation is wanting. On the other hand there is strong ground against such an explanation, as measurements by Adams of a half score of plates in the present series show the same deviations from his 1908 series as the measurements by Ware and St. John. As observations are increased and instrumental equipment varied, it is possible that some unsuspected source of error may come to light that will enable the solar physicist to harmonize the earlier and later results, tho of course it would be more interesting if they should prove to correspond to solar conditions. In the meantime it is very desirable to have an extended series of determinations made by the same measurer and at the same time to keep the instrumental conditions unchanged. This part of the Mount Wilson program already covers five years and it is hoped to continue the program thru a sun-spot cycle. The results for the five-year period are preliminary and are based upon observations of only three months in each year; as yet they show no definite evidence of any regular change during the period covered. It is hoped that when the observations and reductions for all latitudes are compiled a more positive conclusion can be reached. J. S. Plaskett at Ottawa in his valuable contributions to solar-rotation investigations has given much attention to systematic errors of measurement, particularly to those ascribed to personal equation. His conclusion is that the difference between the Mount Wilson 2.05 km. and the Ottawa-Alleghany 2.00 km. is not due to a change

in the velocity of rotation of the Sun but to plate or measurement errors. His discussion necessarily left out of consideration the more serious discrepancy between the early and later Mount Wilson results, which had not at the time been definitely shown.

Adams found for lanthanum and cyanogen lines a lower rotation velocity than the mean, and for $\lambda 4227$ of calcium and the Hα line of hydrogen a higher velocity than for the reversing layer and also less change of velocity with increasing latitude. Except for the Hα line, the measurements were made upon the same plates as those for the reversing layer and hence the relative velocities are free from instrumental errors and temporary disturbances in the solar atmosphere. The differences of level indicated by these lines have been confirmed by observations on *Radial Motion in Sunspots* and from Mitchell's 1905 eclipse observations. The preliminary reductions of the present Mount Wilson series show relatively high velocities for the strong magnesium triplet in the green, for $\lambda 4227$ and for the H and K lines of calcium, and low velocities for lanthanum lines. In observations made elsewhere which fail to show different rotation values for different elements, such lines as $\lambda 4227$ and H and K of calcium, the Hα line of hydrogen, and the strong magnesium triplet have not been observed. There is much evidence that these lines represent high levels in the solar atmosphere, and, as differences in rotational velocity must be related to differences of level, these lines, notwithstanding the difficulties of measurement, offer the most probable means of detecting it.

The question is not so much different velocities for different elements as different velocities for different levels. There is strong evidence that the lines of an element such as calcium, for example, originate at widely different levels, the difference in level corresponding to the great differences in line intensity. The great majority of lines of medium intensity of the common elements originate in not greatly different levels, and for such lines differences in rotational velocity would necessarily be small and correspondingly difficult to detect. For this reason observations upon lines of widely different intensities have been emphasized at Mount Wilson. Unfortunately the lines used by other observers have not in general been so well adapted to determination of differences in level, and this may account for the negative results. That the effect of diffused sky light is to reduce line displacements at the

Sun's limb is taken into consideration by all solar observers. It seems to be a matter that each observing station must determine for itself. Stations at high elevation where a large proportion of the days are clear possess a distinct advantage in this regard. It may be said that there seems to be no ground for attributing the differences between the early and later Mount Wilson observations to diffused skylight. Tests show that the diffused light just outside the solar image is not of sufficient intensity to affect the photographic plate during the exposure times employed. DeLury finds evidence of the effect of overlapping spectra in certain of his observations at Ottawa and attributes to it all differences in rotation values for different lines. To account for such differences as are shown in the Mount Wilson observations requires according to DeLury's estimates a much higher proportion of diffused light than obtains under the ordinary observing conditions on Mount Wilson.

A review of progress shows that the objects aimed at in the study of solar rotation are still far from being attained.

I. The fundamental one is the absolute velocity of rotation at different latitudes. Upon this agreement has not been reached. The differences between observers exceed the probable errors of measurement and are variously attributed to undetected instrumental errors, to personal equation, or to local disturbances in the Sun's atmosphere. As to variation with latitude, the formulae of Faye represent the relation quite satisfactorily, altho data for the higher latitudes are as yet deficient.

II. Until the causes of the unexplained differences are found and eliminated, a possible variation in the rate of rotation can best be studied by a long continued series under constant instrumental conditions and by the same observer. The differences between the 1908 series at Mount Wilson and the present one can hardly be attributed to personal equation or to local disturbances in the Sun. The first seems to be excluded by Adams's measurements in the two series and the second by the probable elimination of local effects in such extended series. In order to make conditions more nearly comparable, it is planned to obtain simultaneous observations with the 1908 and present equipment.

III. Different rates of rotation for different levels in the Sun's atmosphere are shown by all the Mount Wilson series. Differences

depending upon level have not been found by other observers, possibly for the reason that extremes of level have not been under observation.

IV. Disturbances over limited regions of the Sun are of frequent occurrence and are the more in evidence the higher the differentiation of the solar image. This suggests that they are local convection currents and generally present. The determination of the absolute velocity of rotation is greatly complicated by these local conditions, whose occurrence, moreover, makes any effort to detect short-period variations of very doubtful value.

V. The important question of a difference in rotation between the northern and southern hemispheres has been investigated only by Hubrecht, who found evidence of such a difference. This is a point of great interest and need not wait for its solution until all discrepancies between observers are settled, as it is a relative matter for any one observer and instrument, and therefore offers an inviting field of investigation at the present time.